

Sharp dark-mode resonances in planar metamaterials with broken structural symmetry

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We report that resonant response with a very high quality factor can be achieved in a planar metamaterial by introducing symmetry breaking in the shape of its structural elements, which enables excitation of dark modes, i.e. modes that are weakly coupled to free space.

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Metamaterials research has attracted tremendous amount of attention in the recent years. The interest is mainly driven by the opportunity of achieving new electromagnetic properties, some with no analog in naturally available materials. Extraordinary transmission [1], artificial magnetism and negative refraction [2], invisible metal [3], magnetic mirror [4], asymmetric transmission [5] and cloaking [6] are just few examples of the new phenomena emerged from the development of artificially structured matter.

The exotic and often dramatic physics predicted for metamaterials is underpinned by the resonant nature of their response and therefore achieving resonances with high quality factors is essential in order to make metamaterials' performance efficient. However, resonance quality factors (that is the resonant frequency over width of the resonance) demonstrated by conventional metamaterials are often limited to rather small values. This comes from the fact that resonating structural elements of metamaterials are strongly coupled to free-space and therefore suffer significant losses due to radiation. Furthermore, conventional metamaterials are often composed of sub-wavelength particles that are simply unable to provide large-volume confinement of electromagnetic field necessary to support high-Q resonances. As recent theoretical analysis showed, high-Q resonances involving dark (or closed) modes are nevertheless possible in metamaterials if certain small asymmetries are introduced in the shape of their structural elements [7].

In this Letter we report the observation of exceptionally narrow resonant responses in transmission and reflection of planar metamaterial achieved through introducing asymmetry into its structural elements. The appearance of narrow resonances is attributed to the excitation of otherwise forbidden anti-symmetric modes, that are weakly coupled to free-space ("dark modes").

Metamaterials that were used in our experiments consisted of identical sub-wavelength metallic "inclusions" structured in the form of asymmetrically split rings (ASR), which were arranged in a periodic array and placed on a thin dielectric substrate (see Fig. 1). ASR-patterns were etched from 35 μm copper cladding cov-

ering IS620 PCB substrate of 1.5 mm thickness. Each copper split ring had the radius of 6 mm and width of 0.8 mm and occupied a square translation cell of 15×15 mm (see Fig. 1). Such periodic structure does not diffract normal incident electromagnetic radiation for frequencies lower than 20 GHz. The overall size of the samples used were approximately 220×220 mm. Transmission and reflection of a single sheet of this meta-material were measured in an anechoic chamber under normal incidence conditions using broadband horn antennas.

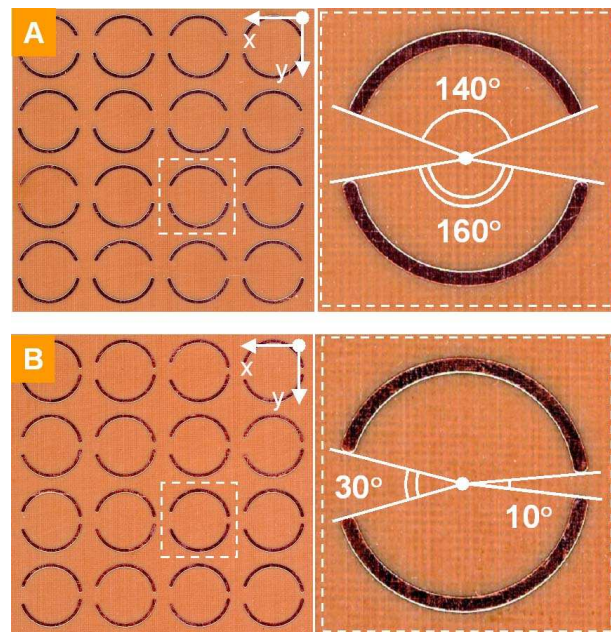


FIG. 1: (Color online) Fragments of planar metamaterials with asymmetrically split copper rings. The dashed boxes indicate elementary translation cells of the structures.

We studied structures with two different types of asymmetry designated as type A and B in Fig. 1. The rings of type A had two equal splits dividing them into pairs of arcs of different length corresponding to 140 and 160 deg (see Fig. 1A). The rings of type B were split along their diameter into two equal parts but had splits of different length corresponding to 10 and 30 deg (see Fig. 1B).

Transmission and reflection properties of structures of both types depended strongly on the polarization state of incident electromagnetic waves. The most dramatic spectral selectivity was observed for electrical field being perpendicular to the mirror line of the asymmetrically split rings, which corresponded to x -polarization in the case of structure A and y -polarization for structure B (as defined in Fig. 1). For the orthogonal polarizations the ASR-structures did not show any spectral features originating from asymmetrical structuring.

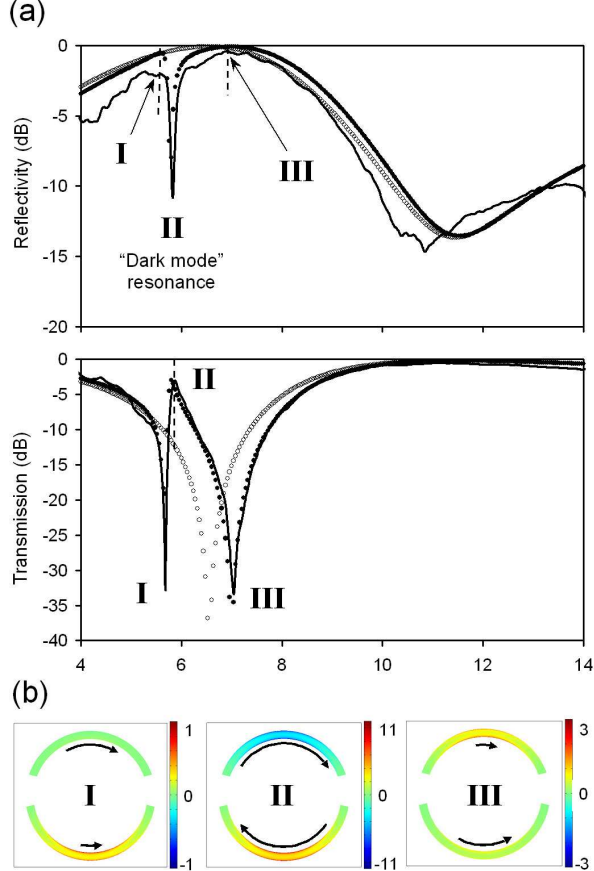


FIG. 2: (Color online) (a) Normal incidence reflection and transmission spectra of A-type metamaterial (presented in Fig. 1A) for x -polarization: solid line - experiment, filled circles - theory (method of moments), empty circles - theory for reference structure with symmetrically split rings. (b) x -Component of the instantaneous current distribution in the asymmetrically split rings corresponding to resonant features I, II and III as marked in section (a). Arrows indicate instantaneous directions of the current flow, while their length corresponds to the current strength.

The results of reflection and transmission measurements of metamaterial A obtained for x -polarization are presented in Fig. 2a. The reflection spectrum reveals an ultra-sharp resonance near 6 GHz (marked as II), where reflectivity losses exceed -10 dB. It is accompanied by two much weaker resonances (marked as I and III) cor-

responding to reflection peaks at about 5.5 and 7.0 GHz respectively. The sharp spectral response in reflection is matched by a very narrow transmission peak reaching -3 dB and having the width of only 0.27 GHz as measured at 3 dB below the maximum. The quality factor Q of such response is 20, which is larger than that of the most metamaterials based on lossy PCB substrates by at least one order of magnitude. On both sides of the peak the transmission decreases resonantly to about -35 dB at frequencies corresponding to reflection maxima.

Fig. 3a presents transmission and reflection spectra of B-type metamaterial measured for y -polarization. A very narrow resonant transmission dip can be seen near 5.5 GHz, where transmission drops to about -5 dB. The corresponding reflection spectrum shows an usually sharp roll-off (I-II) between -4 and -14 dB spanning only 0.13 GHz at around the same frequency. At the frequency of about 11.5 GHz the ASR-structure exhibits its fundamental reflection resonance (marked as III) where the wavelength of excitation becomes equal to the length of the arcs.

To understand the resonant nature of the response, the ASR-structures were modelled using the method of moments. It is a well established numerical method, which involves solving the integral equation for the surface current induced in the metal pattern by the field of the incident wave. This is followed by calculations of scattered fields as a superposition of partial spatial waves. The metal pattern is treated as a perfect conductor, while the substrate is assumed to be a lossy dielectric. For both transmission and reflection the theoretical calculations show a very good agreement with the experimental results assuming $\epsilon = 4.07 + i \cdot 0.05$ (see Fig. 2 and 3, filled circles). For comparison we also modelled metamaterial composed of split rings with no structural asymmetry, i.e. equally split along their diameter. Our calculations indicate that for both polarizations the response of such structure is free from sharp high-Q resonant feature (see Fig. 2 and 3, open circles).

The origin of the unusually strong and narrow spectral responses of the ASR-structures can be traced to so-called "dark modes", i.e. electromagnetic modes that are weakly coupled to free-space. It is this property of the dark modes that allows in principal to achieve high quality resonances in very thin structures [7]. These modes are usually forbidden but can be excited in a planar metamaterial if, for example, its particles have certain structural asymmetry.

Our calculations showed that in the case of structure A an anti-symmetric current mode can dominate the usual symmetric one: at the high-Q transmission resonance, as shown in Fig. 2b (II), two parts of the ring are excited in anti-phase while currents have almost the same amplitude. The scattered electromagnetic fields produced by such current configuration are very weak, which dramatically reduces coupling to free-space and therefore radia-

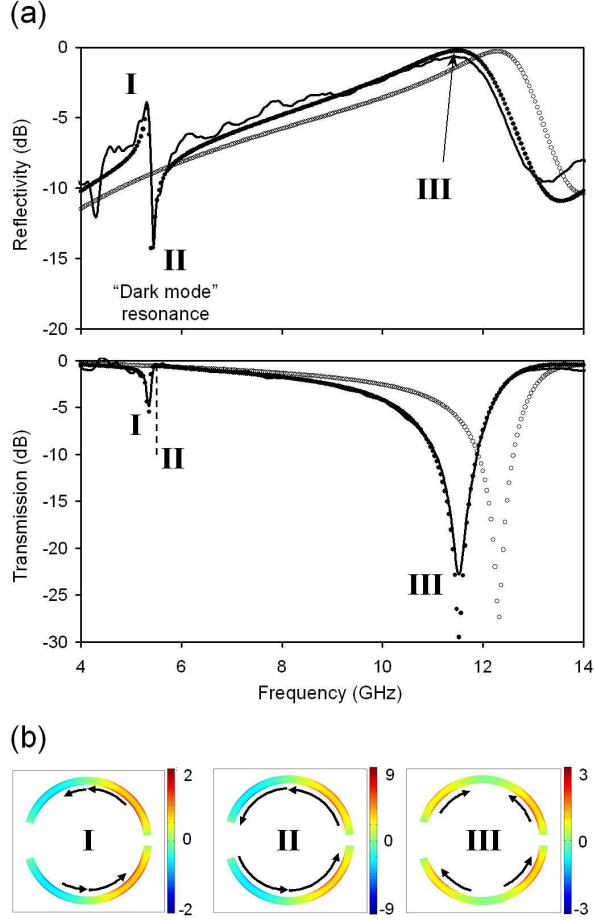


FIG. 3: (Color online) (a) Normal incidence reflection and transmission spectra of B-type metamaterial (presented in Fig. 1B) for y -polarization: solid line - experiment, filled circles - theory (method of moments), empty circles - theory for reference structure with symmetrically split rings. (b) y -Component of the instantaneous current distribution in the asymmetrically split rings corresponding to resonant features I, II and III as marked in section (a). Arrows indicate instantaneous directions of the current flow, while their length corresponds to the current strength.

tion losses. As a consequence, the strength of the induced currents can reach very high values and therefore ensures high quality factor of the response. At the reflection resonances, in contrast to the "dark mode" regime, currents in both sections of the asymmetrically split ring oscillate in phase but excitation of one of the sections dominates the other (see Fig. 2b (I and III)). Importantly, the amplitudes of the currents in this case are significantly smaller than in "dark mode" resonance, which yields lower Q -factors for this type of the response. If the structural asymmetry is removed the anti-symmetric current mode becomes forbidden while two reflection resonances degenerate to a single low- Q resonance state where both parts of the ring are excited equally. Thus introduction of asymmetry in the split-ring structure effectively allows

to create a very narrow pass-band inside its transmission stop-band. This effect is somewhat analogous to appearance of an allowed state in the bandgap of photonic crystals due to structural defects.

Interpretation of the results obtained for structure B appears to be slightly more elaborate. From the symmetry of the split rings it follows that for y -polarized excitation at any frequency current distribution in the opposite sections of the ring should have equal y -components oscillating in phase and equal x -components oscillating in anti-phase. The net current in the ring has therefore always zero x -component, while its y -component can not be fully compensated due to the structural asymmetry. At low frequencies the net y -component is small but it increases significantly as the frequency of excitation approaches 5.5 GHz. At this frequency the wavelength becomes equal to circumference of the split ring and, as shown in Fig. 3b (I), the right side of the ring dominates its left side oscillating in anti-phase. The later results in a resonant increase of the metamaterial reflection (see Fig. 3a). Immediately above this resonance contributions of both sides of the ASR-particle are still in anti-phase but become nearly identical (see Fig. 3b (II)) making the y -component of the induced net current almost zero and therefore dramatically reducing radiation losses (reflection). Further increase of the excitation frequency leads to rise of the reflection until the fundamental resonance of the ASR-structure is reached where the corresponding wavelength is equal to the length of the arcs. In this case both sides of the ASR-particle oscillate in phase and equally contribute to electromagnetic field scattering (see Fig. 3b (III)).

The quality factor of the dark-mode resonances will increase on reducing the degree of asymmetry of metamaterial particles and in case of low dissipative losses can be made exceptionally high. In the microwave region metals are almost perfect conductors and the main source of dissipative losses is the substrate material (dielectrics). Therefore significantly higher resonance quality factors can be achieved for a free-standing thin metal film, which is patterned complementary to ASR-structure, i.e. periodically perforated with ASR-openings. In the visible and IR spectral ranges, however, losses in metals dominate and therefore nano-scaled versions of the original metal-dielectric ASR-structures would perform better. According to our estimates Q -factor of such ASR-nanostructures in the near-IR can be as high as 6.

In summary, we experimentally and theoretically showed that a new type of planar metamaterials composed of asymmetrically split rings exhibit unusually strong high- Q resonances and provide for extremely narrow transmission and reflection pass- and stop-bands. The metamaterials' response has a quality factor of about 20, which is one order of magnitude larger than the typical value for many conventional metamaterials. This is achieved via weak coupling between "dark modes" in the

resonant inclusions of the ASR-metamaterial and free-space, while weak symmetry breaking enables excitation of so-called "dark modes". Achieving the "dark mode" resonances will be especially important for metamaterials in the optical part of the spectrum, where losses are significant and unavoidable. In a certain way such symmetry-breaking resonances in meta-materials resembles the recently identified spectral lines of plasmon absorption of shell nanoparticle appearing due to asymmetry [8].

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